Received 19 Jan
Logged 19 Jan 99

53.301-298

AFRL-SR-BL-TR-99-0061

53.301-298 Standard Form 298, Report Documentation

# REPORT DOCUMENTATION PAGE

OMB No. 0704-0188



**1. AGENCY USE ONLY (Leave blank)**

**2. REPORT DATE**
Dec. 31,1998

**3. REPORT TYPE AND DATES COVERED**
Final Report; 950401-981231

**4. TITLE AND SUBTITLE**
Prediction of Global Cloud Cover
with an Explicit Formulation

**5. FUNDING NUMBERS**
AFOSR
Grant Number
F49620-95-1-0287

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**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution unlimited

**12b. DISTRIBUTION CODE**

**13. ABSTRACT (Maximum 200 words)**

We have successfully implemented an explicit cloud scheme within the Florida State University Global Spectral Model. This includes the liquid water mixing ratio and cloud fractions as two additional dependant variables. The main purpose of this extension is two fold: we wished to improve our global cloud forecasting capability (low, medium and high clouds) and to have a better definition of the cloud radiative effects. A band model is being used for the short and long wave radiative transfer.

A major component of this study is the initialization of clouds. For this purpose we have utilized the U.S. Airforce Real-Time Nephanalysis product called RTNEPH. The microwave radiances from the U.S. Airforce fleet of DMSP satellites is another source of data. These are the special sensor microwave instruments carried by these satellites. This information provides measures of vertically integrated liquid water mixing ratios. The liquid water mixing ratios are vertically partitioned using weights from the RTNEPH; this provides an initial definition of clouds and cloud fractions. These were further initialized using the procedure of physical initialization. The impact studies of this cloud specification and initialization appear very promising.

**14. SUBJECT TERMS**
cloud, RTNEPH, DMSP satellites

**15. NUMBER OF PAGES**

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
| --- | --- | --- | --- |
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | |

DTIC QUALITY INSPECTED 1

FINAL REPORT

AFOSR Project: Prediction of Global Cloud Cover with an Explicit Formulation

Project Number F49620-95-1-0287
Period: April 1, 1995 - December 31, 1998

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**Abstract:**

We have successfully implemented an explicit cloud scheme within the Florida State University Global Spectral Model. This includes the liquid water mixing ratio and cloud fractions as two additional dependant variables. The main purpose of this extension is two fold: we wished to improve our global cloud forecasting capability (low, medium and high clouds) and to have a better definition of the cloud radiative effects. A band model is being used for the short and long wave radiative transfer.

A major component of this study is the initialization of clouds. For this purpose we have utilized the U.S. Airforce Real-Time Nephanalysis product called RTNEPH. The microwave radiances from the U.S. Airforce fleet of DMSP satellites is another source of data. These are the special sensor microwave instruments carried by these satellites. This information provides measures of vertically integrated liquid water mixing ratios. The liquid water mixing ratios are vertically partitioned using weights from the RTNEPH; this provides an initial definition of clouds and cloud fractions. These were further initialized using the procedure of physical initialization. The impact studies of this cloud specification and initialization appear very promising.

## Introduction:

The objectives of this research supported by AFOSR were to develop a physically based cloud scheme and to improve cloud forecasts with a large-scale model. Towards this goal a prognostic cloud scheme has been developed and incorporated into the Florida State University Global Spectral Model (FSUGSM) via the introduction of a cloud parameterization which includes cloud water/ice content and cloud fraction. The time evolution of clouds is defined through the large-scale budget equations for cloud water content and fractional cloud cover. The scheme considers the formation of clouds in connection with large-scale ascent, diabatic cooling, boundary-layer turbulence, and vertical transport of cloud water from convective updrafts. Clouds dissipate through adiabatic and diabatic heating, turbulent mixing of cloud air with unsaturated environment air, and depletion of cloud water by precipitation. Unlike conventional schemes, the scheme is fully prognostic and model consistent. Furthermore, the formation of anvil and cirrus clouds originating by cumulus updrafts and boundary-layer clouds is included.

## Details of Analysis:

Operational analyses from the National Center for Environmental Prediction (NCEP) provide initial conditions for model integrations. The NCEP analyses consist of geopotential height, temperature, zonal and meridional wind on 12 mandatory pressure levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, and 50 mb), and relative humidity on the six lowest levels. The gridded analyses are vertically interpolated to the model's $\sigma$ surfaces (for RH a constant value is used above 300 mb), and expanded in the spherical harmonic basis functions of the global spectral model. A diabatic nonlinear normal mode initialization is used.

Cloud data used for development and verification of cloud schemes were the Real-Time Nephanalysis (RTNEPH) obtained from Air Force Globla Weather Control via the NCEP data facility. The RTNEPH data set includes a global analysis of cloud amount, cloud type, cloud bases and tops based on satellite and conventional observations. This provides us with unique data source for the cloud initialization.

The RTNEPH analysis is done with respect to polar-stereographic grids of the northern and southern hemispheres with a horizontal resolution 47.625 Km true at 60 degree north and south latitude. Data sources for the analysis are primarily the infrared (IR) and visible (VIS) channels on two Defense Meteorological Satellite Program (DMSP) satellites, with some information obtained from polar-orbiting satellites(e.g. NOAA 11/12) and surface observations, when available. A manual bogus is also employed during each analysis cycle. The RTNEPH data set consists of total cloud and up to 4 distinct layered clouds. Each pixel point contains cloud coverage, geopotential height of the layered cloud bases and tops, cloud type, time of observation, and other diagnostic information. Details are described in Hamill *et. al.* (1992).

### Three-dimensional cloud fraction

Heights of cloud tops and bases, and cloud amounts are the primary source of global and vertical distribution of cloud fraction. Three-dimensional cloud fraction is derived on the sigma coordinate at the gaussian grid for use in the model initialization and verification. The coordinate transformation from the polar-stereographic grid to the gaussian grid is carried out in both hemispheres.

The gridded field of geopotential height on 12 mandatory pressure levels is horizontally interpolated to the gaussian grid. The heights of cloud bases and tops and the cloud amounts of each layered cloud are decoded from the compressed RTNEPH data set in both hemispheres. Since RTNEPH cloud height is measured from the mean sea level, terrain height should be added to obtain the ground-based cloud height at each grid point. In-cloud pressures are obtained by interpolating geopotential heights of the mandatory pressure levels to the height of the grid clouds. Given surface pressure, we can directly calculate corresponding sigma values of cloud bases and tops for each cloud. Once we have sigma values of cloud base and top, we assign corresponding cloud amount onto sigma levels throughout each layered cloud.

Total clouds are computed by using the method of random overlap through the column as

$$N_T = 1 - \prod_{k=1}^{K} \left(1 - N_k\right) \tag{1}$$

where $N_T$ is total cloud, $N_k$ denotes the cloud fraction on each sigma level, and $k$ is taken to be 14 in this study. The random overlap method is also applied to obtain the low, middle and high clouds, respectively. The low level clouds are assumed to exist between $\sigma = 0.9$ and $\sigma = 0.7$ levels, the middle level clouds between $\sigma = 0.7$ and $\sigma = 0.4$, and the high level clouds between $\sigma = 0.4$ and $\sigma = 0.1$.

Three-dimensional cloud liquid water content

In the present study we proposed a method to obtain a vertical distribution of cloud LWC from the three-dimensional RTNEPH cloud data by using the algorithm of Ackerman and Cox(1987) as will be briefly described in this section. Although the algorithm is rather rough, no attempt has been made in this way. For verification of the derived LWC and model validation, LWP retrieved from SSM/I is used.

Based on a compilation of observational studies, Ackerman and Cox proposed that cloud LWC may be represented as a function of cloud-top pressure. They provided a relationship between LWC and cloud-top pressure. We use their function to represent cloud LWC with respect to model sigma-level pressure:

$$\mathrm{LWC} = \begin{cases} 10^{(p-750)/320} & \text{for } p < 750\text{ mb} \\ 1.0 & \text{for } p \geq 750\text{ mb,} \end{cases} \tag{2}$$

where LWC is given in $g/m^3$ and $p$ is model sigma-level pressure in cloud in *mb*.

In this research we assume that LWC is a function of pressure only within cloud base and cloud top. However, a cloud depth in this work is represented by a sigma value of cloud bases and tops. In order to apply the Ackerman and Cox equation as a vertical structure function to derive the vertical profile of cloud liquid content we need to obtain pressure values corresponding to each sigma-levels in cloud multiplying by surface pressure at the point. The temperature field from the NCEP analyses are horizontally interpolated to gaussian grid on the pressure level and are used to calculate a density of air for each cloud sigma-level. Liquid water mixing ratio inside cloud is obtained dividing liquid water content by air density. First estimates of the vertically integrated liquid water mixing ratio are computed by the expression as

$$\mathrm{TLW} = \frac{P_s}{g}\int_0^1 l\,d\sigma \tag{3}$$

where *TLW* is total liquid water $\left(\mathrm{Kg/m^3}\right)$, $P_s$ surface pressure *(hPa)*, *g* gravity $\left(\mathrm{m/sec^2}\right)$, and *l* liquid water mixing ratio $\left(\mathrm{Kg/Kg}\right)$. Next, the cloud liquid water mixing ratio is normalized by total liquid water to obtain the vertical weighting functions. Finally, the satellite-inferred liquid water path is projected onto the vertical weighting functions to derive the horizontal and vertical distribution of the cloud liquid water mixing ratio.

**Results:**

Experiments have been conducted to evaluate the RTNEPH analyses (retrievals of three level clouds and total cloud) and its impact on cloud initialization with the diagnostic and prognostic cloud scheme.

RTNEPH Analyses

Fig.1 shows the zonally averaged 8-day mean cloud cover for high, middle, low and total cloud processed from the RTNEPH data sets through the procedure described in the previous section compared with surface-based observations analyzed over land by Warren *et. al.*(1986). The surface observations were compiled from an eleven year data set extending from 1971 through 1981. In Fig.1 all level clouds as well as total cloud derived from RTNEPH depict very well (1) the dense cloud cover over and around the equator associated with the Inter-Tropical Convergence Zone (ITCZ), (2) the minimal coverage in the subtropics in both hemispheres, and (3) the peaks in cloudiness near 60° N and 60° S. In addition, total cloudiness shows very good agreement with the climatology. Global averages for high, middle, low and total clouds analyzed from RTNEPH are 15%, 25%, 43% and 58%, respectively. The global average value of 58% for RTNEPH total cloud is close to the 56% estimated in ISCCP (Rossow and Schiffer, 1991). The biases between the total clouds as reported from the RTNEPH data and those computed here by overlapping of three level clouds are small (8.5%). This analysis suggests that the compaction methodology proposed here to retrieve the level clouds from RTNEPH database is acceptable for use in this research.

Impact of diagnostic cloud initialization

Initialization for the diagnostic cloud scheme is carried out during a pre-integration phase between day-1 and day 0 using the T106 FSUGSM. A modification of the initial state variables via incorporation of analyzed cloud data is accomplished during this assimilation phase of the model forecast. This is complimented by a Newtonian relaxation of all the basic variables of the model. During the assimilation phase, ingestion of the observed clouds is performed every six hours. Observed clouds are obtained from the algorithm outlined in the previous section. We hypothesize a unique relationship between the cloud amount and the mean relative humidity. The observed relative humidity can then be directly obtained from the observed cloud amount via the reverse form of the diagnostic cloud fraction equation. Specifically, the formula used is

$$\overline{RH}_{H,M\,or\,L} = RH_c + (1 - RH_c)\sqrt{N_{H,M\,or\,L}} \tag{4}$$

where $\overline{RH}$ is the mean relative humidity in a layer corresponding to level clouds.

The model relative humidity is nudged towards the observed relative humidity every timestep by assuming a linear tendency between the six hourly observations. The matching is based upon the ratio of observed relative humidity to model relative humidity, which is given as $\gamma = RH_{obs}/RH_{model}$. In order to avoid an abrupt change in the model's moisture field, the parameter $\gamma$ is constrained to fall within the range [0.97, 1.03]. The model moisture variable $q$ is modified by the relation

$$q = \mathrm{Min}(\gamma q, RH_{obs} * q_s)$$

This cloud initialization is carried out between 60° N and 60° S domain.

Prior to discussing the cloud initialization, it is of interest to examine the correlation between cloud amount by the diagnostic cloud fraction formula and that from RTNEPH by means of the proposed retrieval method. This was done for both physically initialized data (PI) and data only subjected to normal mode initialization (NI). We find that for total cloud the data with normal mode initialization has a 0.34 correlation while the physically initialized data has a 0.42 correlation with the RTNEPH data.

Cloud initialization with the diagnostic cloud scheme was carried out for the period 00Z Oct. 1 - 00Z Oct. 2, 1995. Plotted in Fig. 2 are time series of the correlation between the model-produced clouds and the observed clouds during the cloud initialization phase for high, middle, low and total clouds, respectively. The correlation between cloud-initialized (CI) total cloud and RTNEPH total cloud is over 0.90. The improvement due to cloud initialization is readily apparent with much higher correlation coefficients for all level clouds compared to no-cloud initialization (PI) run. Performance of the initialization for high clouds is not as good as for middle and low clouds. A possible reason for this may be that the matching process between the model relative humidity and RTNEPH-derived relative humidity is very slow due to smaller amounts of model high cloud. This can be attributed to a lack of sources for high cloud, such as convective activity in the model. Fig. 3 illustrates the zonal mean total cloud cover for PI, CI and RTNEPH at the initial time 00Z Oct. 2, 1995. Over the cloud initialization domain (60° N – 60° S) total cloudiness from CI agrees very well with the observed (RTNEPH) total cloud cover.

Sensitivity of cloud predictive skill has been tested in the T106 FSUGSM using both the cloud initialized data (CI) and the uninitialized data (PI). Six day forecasts were made starting at 00Z Oct. 2, 1995. Fig. 4 plots the correlation between the model-produced clouds and the observed clouds for both PI and CI forecasts. For CI the cloud predictive skill rapidly decreases from the initial value of 0.93 to 0.47 during the first 24 hours of the forecast. The rapid decrease in cloud forecast skill may reflect the weak physical basis underlying the diagnostic cloud scheme. That is, these results may suggest a lack of uniqueness in the relationship between cloud fraction and model variables as compared to the RTNEPH data. Beyond day 2.5 no difference can be discerned in the cloud evolution between two experiments.

Impact of Prognostic Cloud Scheme

Sensitivity of cloud predictive skill was tested in the FSUGSM prognostic cloud model with the initial state of cloud liquid water content and cloud amount. Six day forecasts were made beginning at 0Z on October 2, 1996. Shown in Figure 5 are time series of the correlation between the prognistic model produced clouds and the RTNEPH retrieved clouds for all days of forecast for high, middle, low and total cloud respectively. Correlations for all model clouds except for middle cloud are higher than 0.6 during the six day forecast. High cloud has the highest correlation since the model has a coarser resolution in the upper troposphere than in the lower troposphere. The values for global mean cloud cover of observed and predicted high, middle, low and total cloud are shown in Figure 6. All predicted clouds are fairly consistent during the period of forecast as compared to the observed clouds. This is an indication of the stability of the FSU prognostic cloud model.

## Publications resulting from this award

Krishnamurti, T.N., Saad Mohalfi, H.S. Bedi, and S. Cocke, 1998: Sensitivity of synoptic systems and diurnal change to dust aerosols over the region of Saudi Arabia. *Monthly Weather Review*,**126**, 3153-3168.

Krishnamurti, T.N., H.S. Bedi and W. Han, 1998: Organization of convection and monsoon forecasting. *Meteorology and Atmospheric Physics,* **67**, 117-134.

Krishnamurti, T.N., H.S. Bedi, G.D. Rohaly, D.K. Oosterhof, R.C. Torres, C.E. Williford and N. Surgi, 1997: Physical Initialization. *Atmosphere-Ocean,* **35**, 369-398.

Krishnamurti, T.N. and H.S. Bedi, 1996: A brief review of physical initialization. *Meteorology Atmospheric Physics,* **60**, 137-142.

Krishnamurti, T.N., H.S. Bedi, D. Oosterhof and G. Rohaly, 1996: Atmospheric budget during a Bangladesh flood event. *International Journal of Climatology*, **16**, 791-803.

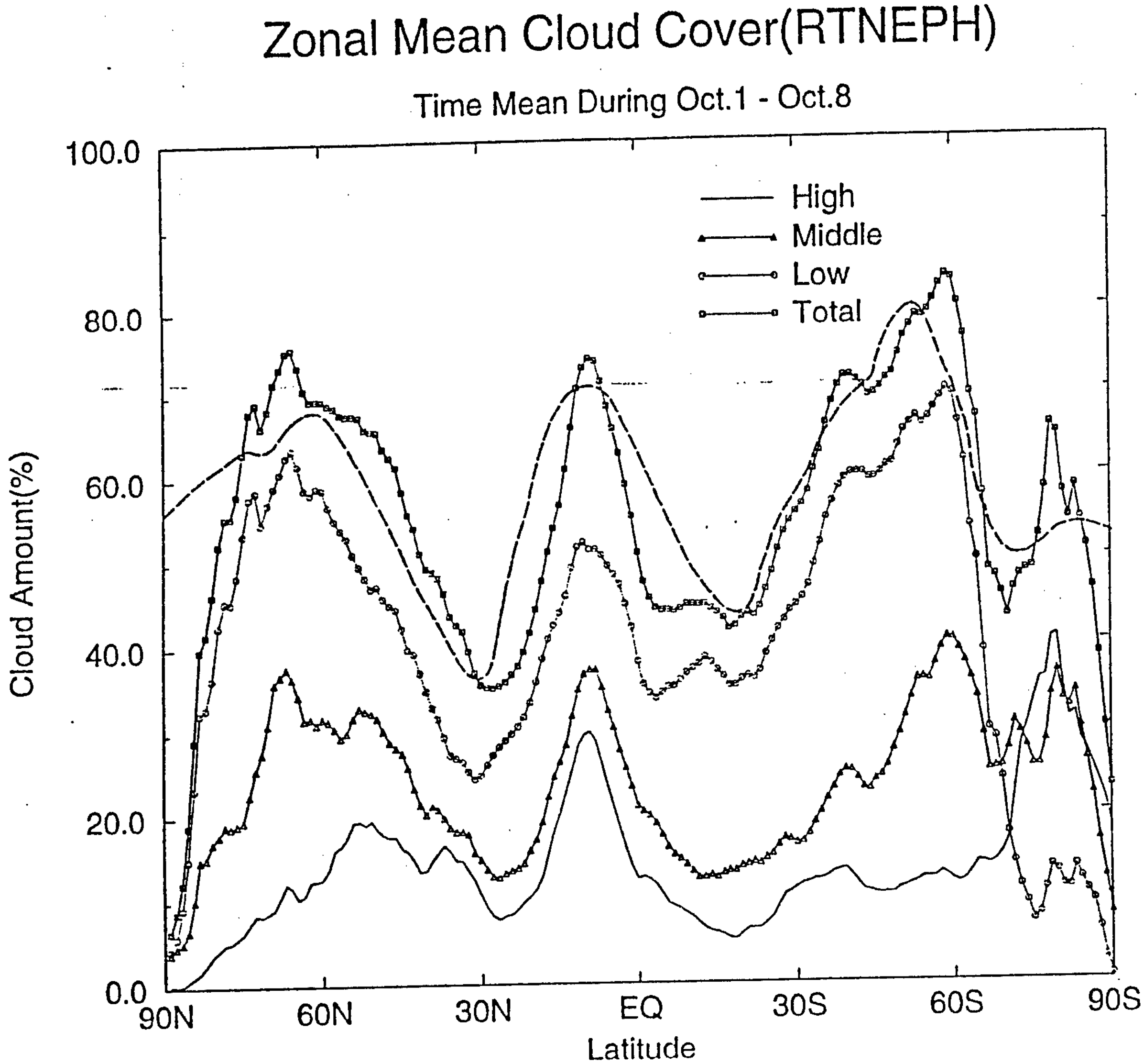
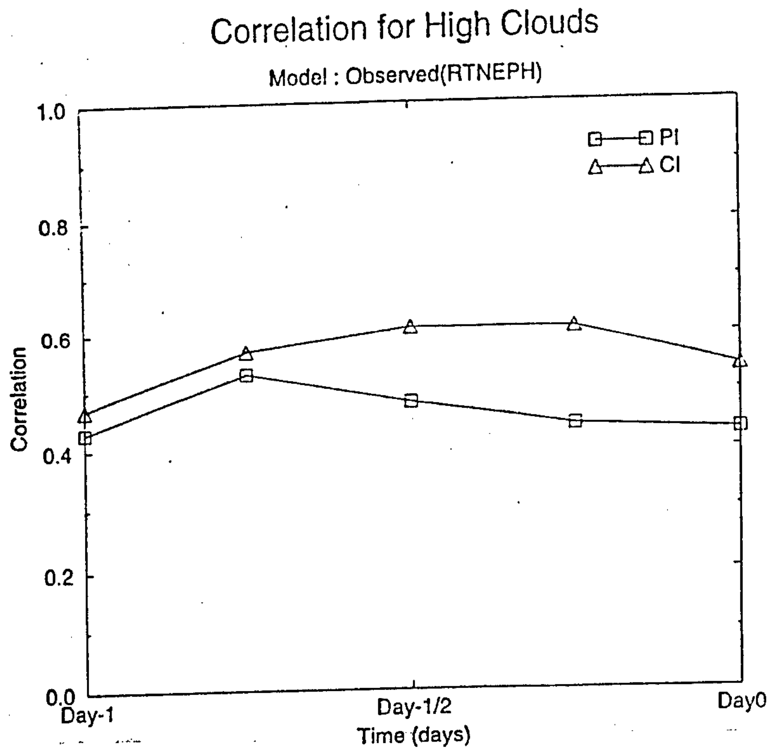



Fig. 1. The zonally averaged 8-day mean cloud cover processed from the RTNEPH datasets. Solid line indicates high; triangles for middle; circles for low; squares for total cloud. Dashed lines represent total cloud for the climatology for total cloud cover(Warren et al., 1986).



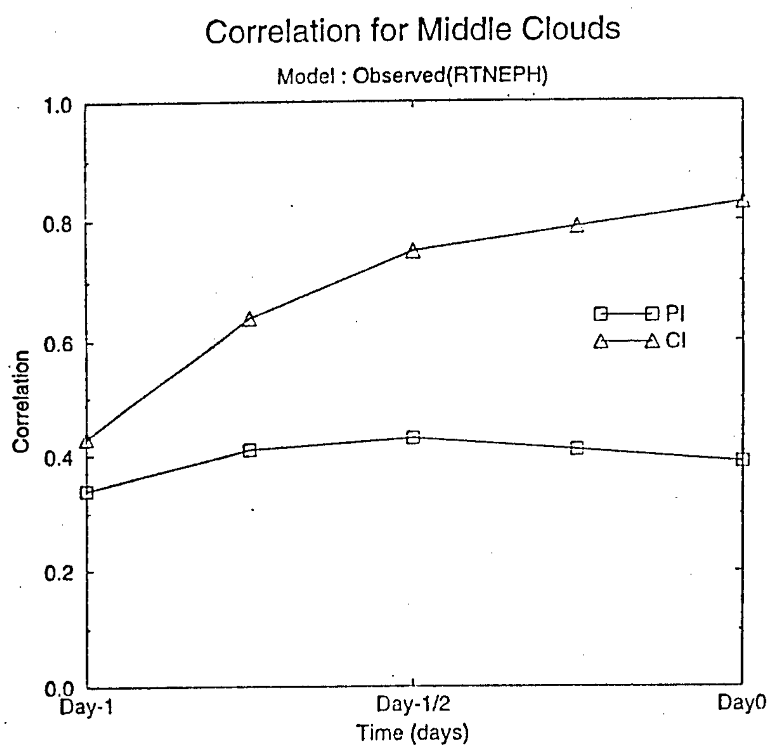
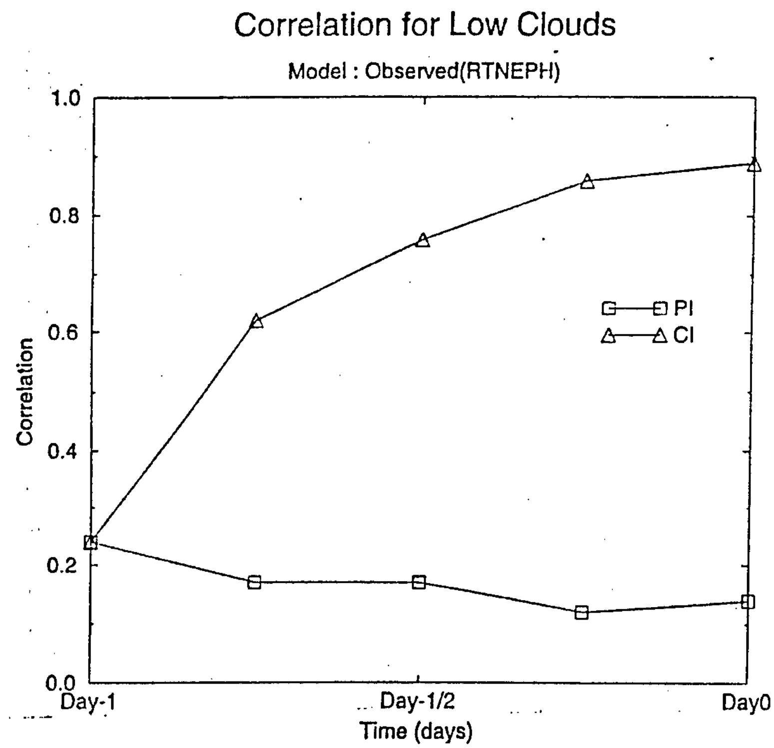
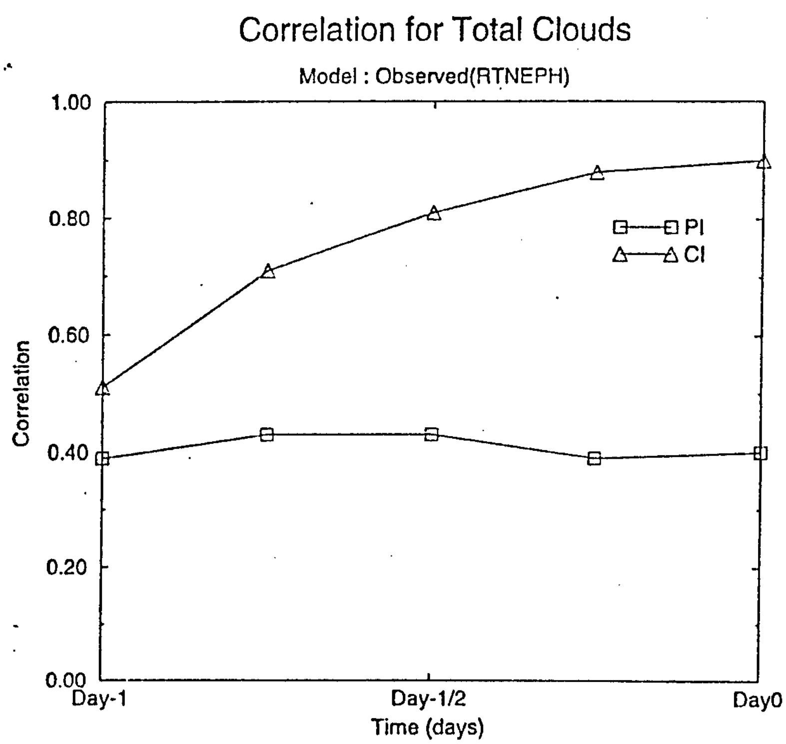




Fig. 2. Time series of the correlation between the model-produced clouds and the observed clouds during the cloud initialization phase for high, middle, low and total clouds, respectively.

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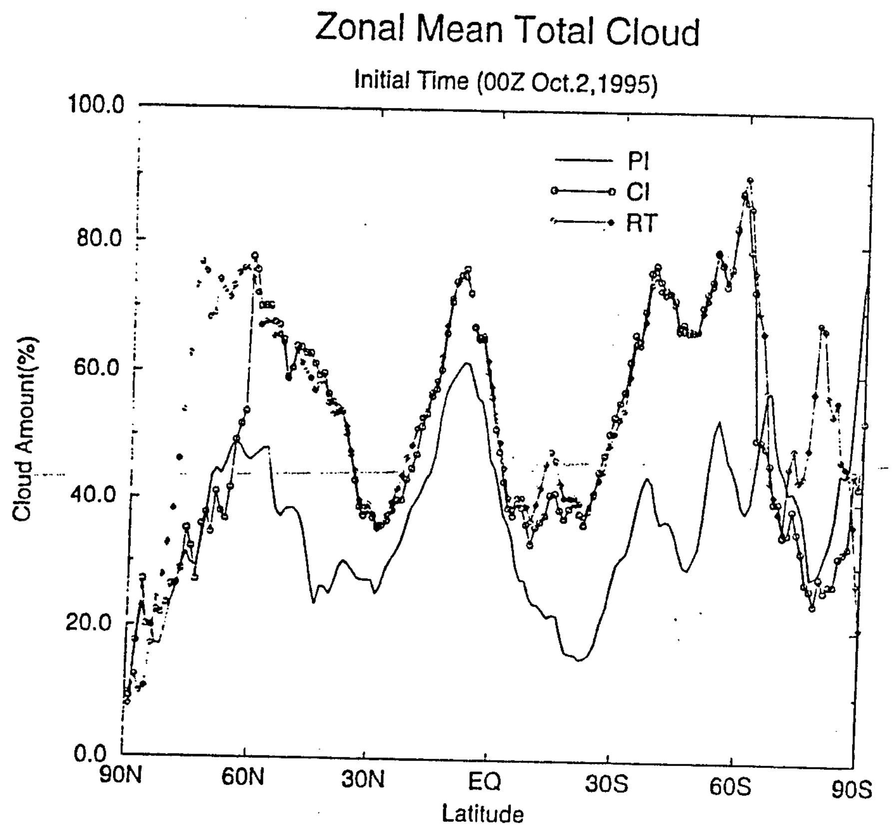


Fig. 3. The zonal mean total cloud cover for no-cloud initialization (PI), cloud initialization (CI) and observations (RTNEPH) at the initial time 00Z Oct. 2, 1995. Solid line indicates PI; circles for CI; rectangles for RTNEPH.

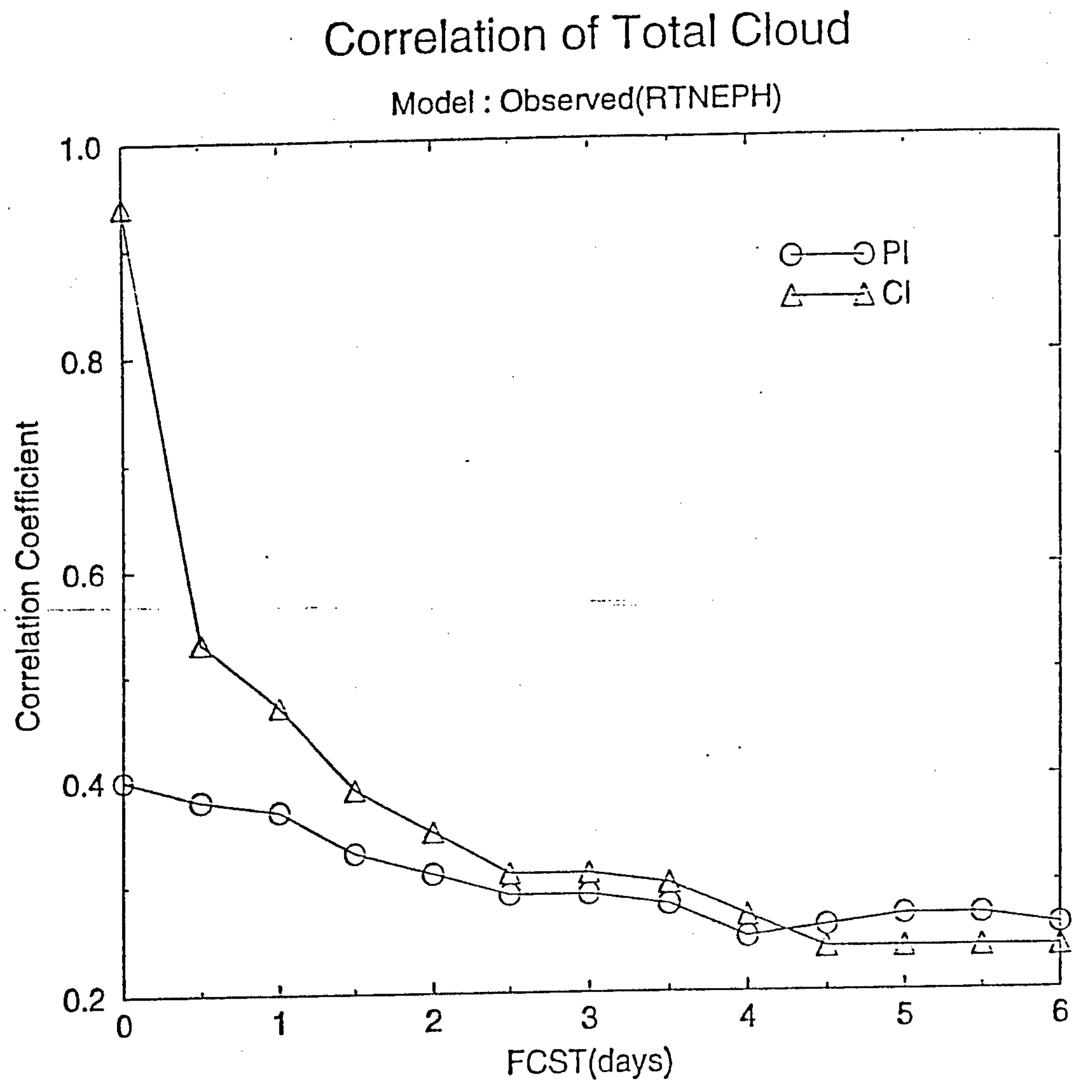


Fig. 4. Correlation between the model-produced clouds and the observed clouds for both PI(squares) and CI(triangles) during the forecast.

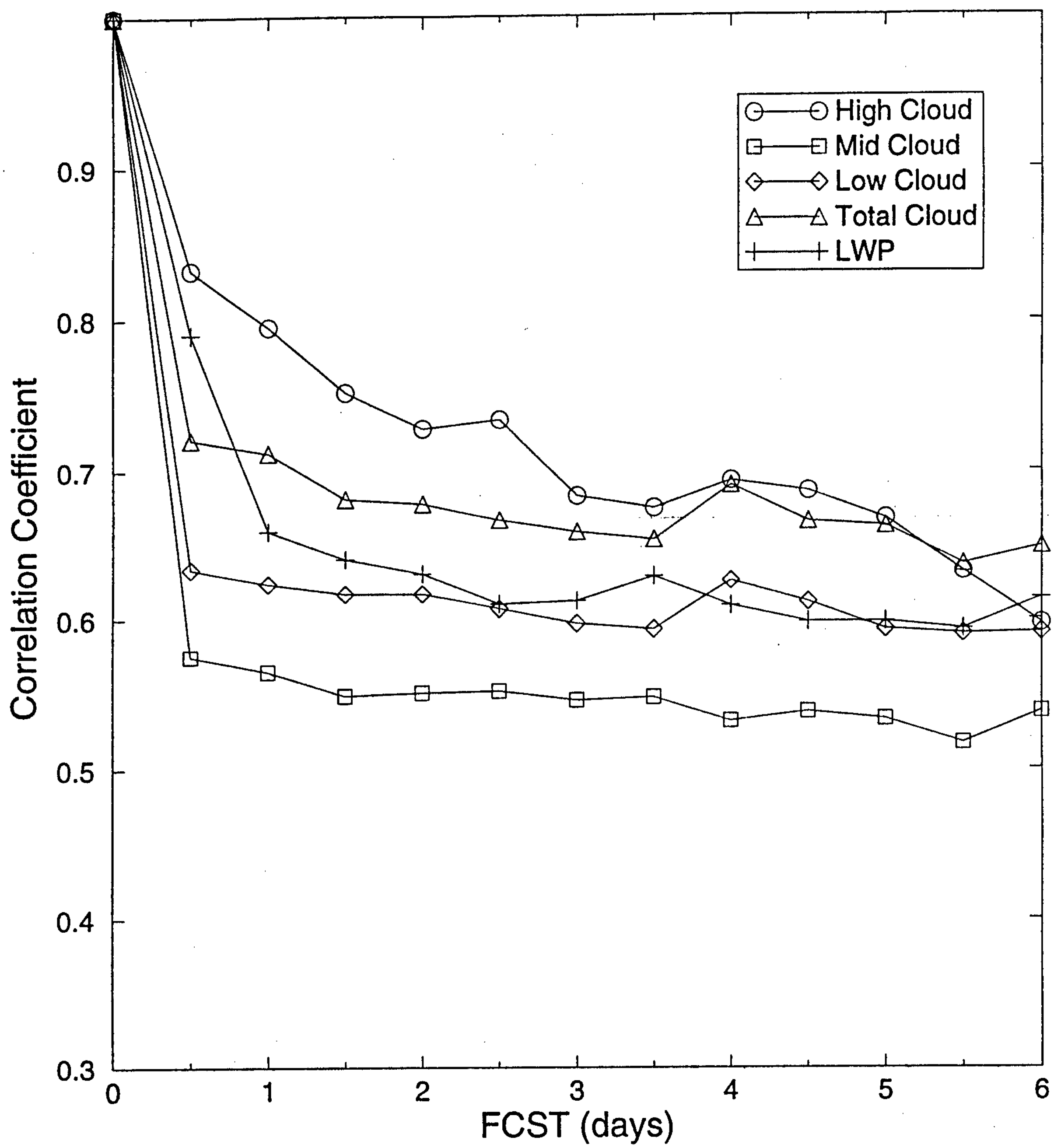


Figure 5: Correlation of cloud using the prognostic scheme

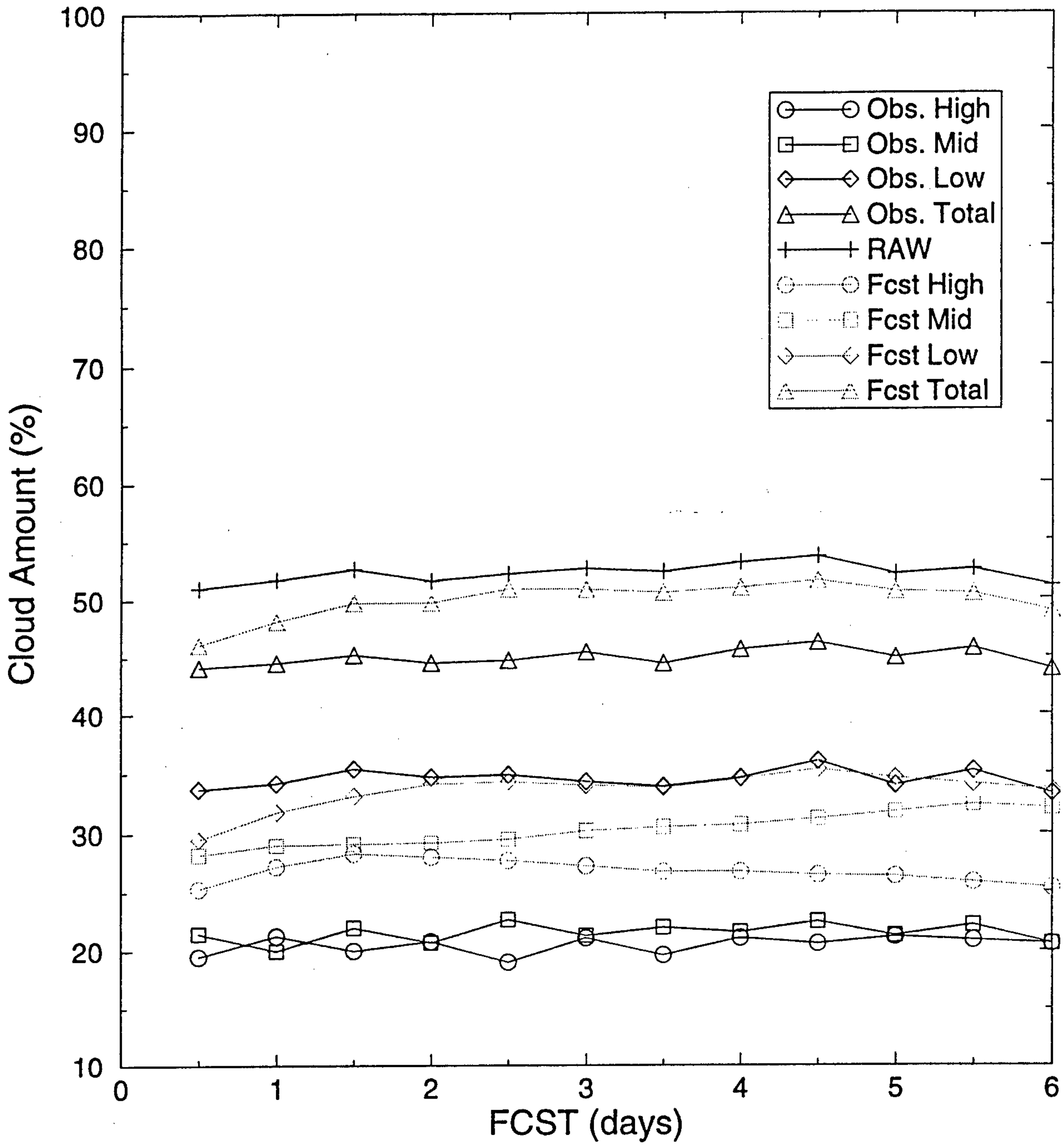


Figure 6: Global mean of cloudiness vs. day of forecast for the prognostic cloud scheme